

Vehicle manufacturing water use and consumption: an analysis based on data in automotive manufacturers' sustainability reports

John Semmens · Bert Bras · Tina Guldberg

Received: 3 December 2012 / Accepted: 3 June 2013 / Published online: 18 June 2013
© Springer-Verlag Berlin Heidelberg 2013

Abstract

Purpose The goal of this study is to develop an estimate of water use and consumption in automotive manufacturing to enhance the data quality of vehicle life cycle assessments that include life cycle water impacts. A benchmark is developed to compare water resources across manufacturing and nonproduction-related manufacturing processes, including an indication whether indirect water consumption due to electricity generation is significant.

Methods Data from 12 original equipment manufacturers' (OEM's) sustainability reports are examined for the years 2006 to 2010. Distinctions are made between "water use" and "water consumption." These factors are divided by total reported production to develop use and consumption values in cubic meter/vehicle for comparison. Additionally, total energy consumption is converted to indirect water consumption based on the water consumed in the generation of electricity for the electricity grid mix.

Results and discussion Excluding outliers, average direct water use is 5.20 and 5.95 m³/vehicle for manufacturing and company-wide activities, respectively, with corresponding standard deviations of 1.42 and 1.20 m³/vehicle. Average direct water consumption was calculated to be 1.25 and 4.29-m³/vehicle for manufacturing and company-wide activities, respectively, with corresponding standard deviations of 0.52

and 1.56 m³/vehicle. Average indirect water consumption due to electricity consumption is found to be 2.21 m³/vehicle. Variability arises through different understandings on the words "consumption" and "use," reporting continuity between years and in classification of data as it relates to manufacturing, nonmanufacturing, or company-wide activities.

Conclusions These water values show that needs vary widely across OEMs. Additionally, the magnitude of the indirect water consumption results indicates that OEMs should focus on both indirect and direct water consumption to reduce their overall water footprint. The results also highlight the potential for significance and variability in indirect water consumption, in particular for "cradle-to-gate" type of impact assessments, dependent on electricity generation water consumption assumptions. It is hoped that with the introduction of water reporting standards like the International Organization of Standardization 14046, manufacturers will provide a more comprehensive summary of their water use and consumption in the future.

Keywords Automotive · Electricity · Inventory · Water consumption · Water use

Abbreviations

LCA Life cycle assessment
OEM Original equipment manufacturer
ISO International Organization of Standardization
VMA Vehicle manufacturing and assembly

Responsible editor: Adriana Del Borghi

Electronic supplementary material The online version of this article (doi:10.1007/s11367-013-0612-2) contains supplementary material, which is available to authorized users.

J. Semmens · B. Bras (✉)
George W. Woodruff School of Mechanical Engineering, Georgia
Institute of Technology, Atlanta, GA 30332, USA
e-mail: bert.bras@me.gatech.edu

T. Guldberg
Georgia Tech Manufacturing Institute, Atlanta, GA 30332, USA

1 Introduction

1.1 Motivation

In 2010, the International Organization of Standardization (ISO) launched a working group to develop ISO 14046,

entitled *Water footprint—Requirements and guidelines*, a standard on principles and guidelines for water footprinting of products, processes, and organizations (Raimbault 2011). The scope of ISO 14046 is to formalize the calculation and reporting of water footprinting as one impact indicator within a more comprehensive environmental assessment (ISO 2011). Need for this standard has arisen due to the increasing water scarcity and growing water demand in many regions around the world. Such standards are especially pertinent to multinational corporations with a need to manage water throughout their diverse global manufacturing operations. Standardized water footprinting would allow these organizations to conduct meaningful comparisons of internal activities and benchmark against competitors' operations. The automotive industry with its diverse and global supply chain specifically stands to benefit from this resource as a support tool for national planning strategies, reducing water and electricity inputs, and evaluating social and governmental policies.

Even without ISO 14046, many automotive manufacturers recognize the importance of water footprinting and report some water data in their annual sustainability reports. As will be shown, however, reporting practices are varied and inconsistent, and care must be taken in interpreting the data presented so that meaningful comparisons can be developed. Reporting of water data are also often lacking by comparison with other environmental metrics such as carbon footprinting and life cycle assessment (LCA) per ISO 14040 and ISO 14044. We demonstrate the necessity of such standards in relation to the automotive industry for reporting water use and consumption in the manufacturing process.

Water use and consumption directly under the control of the OEM in are the focus of this study. We attempt to develop a meaningful comparison of manufacturing water use and consumption data using information reported by 12 OEMs (auto manufacturers) in their annual sustainability reports from 2006 through 2010. The goal is to compare available manufacturer's water use and consumption data on a per-unit (vehicle produced) basis and assess their variability. Some manufacturers—BMW, Ford, and Toyota—report water data in this form. Others—Nissan, Hyundai, and Chrysler—provide information on water inflows and wastewater discharges requiring production data to calculate per unit use/consumption. We examine the different activities where water is utilized to determine the proportion of water use and consumption in the manufacturing process versus nonmanufacturing activities. It should also be noted that when considering manufacturing, these water values only include in-house operations and do not represent parts production completed by suppliers. Thus, when considering the total water use or consumption associated with any particular vehicle, further parts production information is necessary in addition to the results presented here (Tejada et al. 2012b).

1.2 Definitions and literature review

For the analysis presented in this paper, we distinguish between water use and water consumption. The following definitions are used:

- *Water use* is defined as all water that goes into a system. Most of this typically leaves the system as wastewater.
- *Water consumption* is defined as freshwater withdrawals which are evaporated or incorporated in products and waste and therefore do not return to the source of origin. The water molecule is not available in liquid form for (re)use after it is consumed, at least not immediately. The difference between the amount of input water (water use) and wastewater is the water consumption.

Similar definitions are given by Owens and ISO 14046 who define consumption as water resource quantities that are denied to others (Owens 2002) or water withdrawal where release back to the source of origin does not occur (ISO 2011). This is an important distinction because, depending on how water consumption is defined, the results of the water footprint for a given life cycle study may alter significantly. Some authors include water transferred into different watersheds, or disposed into the sea after use, into the definition, (e.g., Pfister et al. 2009). In principle, any wastewater from process operations can be brought back to the same locality with equal or better quality as the input water. Yet the cost of such operations can become prohibitive depending on the process and quality of the wastewater output. Water that is included in the product or evaporated during the process is completely lost from the current locale, however, and thus represents a worst-case scenario.

We also distinguish between direct and indirect water consumption, similar to a financial accounting view of direct and indirect costs:

- *Direct water consumption* can easily be traced to a specific manufacturing activity or process, similar to direct materials or costs. For example, we consider water consumed during the painting process (when cleansing the surface of the vehicle) as direct water consumption.
- *Indirect water consumption* represents water consumed by products or processes under the control of the OEM but external to the vehicle manufacturing process. For example, electricity generation consumes water. When OEMs in turn utilize this electricity for manufacturing purposes, we consider this a form of indirect water consumption.

These distinctions are important for our comparison of water consumed in the vehicle manufacturing process—either directly through water inputs to the system or indirectly through electricity consumption. Electricity consumption is specifically examined because of its potential impact and availability in automotive sustainability reports.

The United States Geological Survey (USGS) and other authors have studied the amount of water use (withdrawal) for different industrial sectors in the US estimates from 2000 have shown that of the 140,000 billion gallons of direct withdrawals, a large majority of water is used for power generation (47.8 %), followed by irrigation (33.6 %), nondomestic public supply (5.1 %), and industrial water use (4.8 %) (Blackhurst 2010). While both direct and indirect water use has been considered for several of these largest use sectors, power generation and agricultural water use dominate, and little information is available for industrial activities like automotive manufacturing. In 1995, similar industrial *use* levels were reported as 6.7 % of total US water withdrawals (Owens 2002). In that same year, industrial *water consumption* was estimated at 15 % of the total US consumption (~47 billion gallons/year) (Owens 2002). Clearly, aggregate industrial water use has declined as process technologies and awareness on water impacts improve, but industry-specific use and consumption—such as in automotive manufacturing—is poorly documented.

Most vehicle life cycle studies focus on energy use or carbon emissions, not on water consumption. Those that do mention water consumption are generally limited to case studies of a specific plant, location, or vehicle. In Tejada et al. (2012b), we performed and documented a life cycle inventory for water consumption for a given vehicle. Large differences in water use versus consumption were noted. A breakdown of water consumption by life cycle phase is given in Table 1 (Tejada et al. 2012b). In Table 1, it is apparent that manufacturing water consumption (e.g., parts production of 902 L and vehicle assembly of 670 L) is greatly overshadowed by the almost 52,000 L of water consumed in the extraction and production of fuel consumed during the use phase. In Tejada et al. (2012a), we added indirect water consumption due to electricity generation to the material and manufacturing phases and noted that the water consumption of electricity generation was significant in automotive manufacturing, ranging from 4,500 to potentially 25,000 L/vehicle for manufacturing and assembly electricity use (Tejada et al. 2012a).

A report by Volkswagen detailing a 10-year life cycle inventory of four VW Golf A4 variants echoes these inventory

results. In Schweimer and Levin (2000), it is reported that “water consumption of 95 m³ (95,000 l) per car can be broken down into that needed for electric power generation (46 m³), fuel production (23 m³), car washing (8 m³), material production (10 m³) and other factors (9 m³).” The report also comments on the lack of references available for comparison. Of greatest interest here is the water consumption from material production and electric power generation that could be attributable to manufacturing activities.

Another study of three Volkswagen models followed an impact-oriented water footprint method to quantify freshwater consumption. Water inventories for the Polo, Golf, and Passat car models were created, and the resulting human health, ecosystems, and water resource impacts over the life cycle of the vehicles were examined. Water consumptions ranged from 52 to 83 m³/car, with the Polo generally having the smallest water impact and Passat the greatest (Berger et al. 2012). Interestingly, this study indicated that 95 % of water was consumed during the production phase, predominantly due to material production. This is contrary to the findings by Tejada et al. (2012b) which cited the use phase as the primary consumer of water because of the water needed for oil exploration and fuel production. These differences highlight the lack of standardization inherent in current water-focused life cycle inventory (LCI) and LCA data and studies.

The studies in Schweimer and Levin (2000) and Tejada et al. (2012a) support the USGS estimates that the production of energy for the life of a vehicle is an important consumer of water. Many other authors identify the importance of water in energy generation, e.g., Feeley III et al. (2008), Fthenakis and Kim (2010), and Gleick (1994). Fossil fuels used in energy production require large quantities of water for extraction or mining and can be produced in water-stressed localities. Water is also required for processing, refining, and distributing these fuels as well as for cooling and maintenance of thermoelectric power plants where they are burned (Yen and Bras 2012).

Thus, although most water may be consumed and used in the production of fuels for the use phase of the vehicle, the preceding analyses indicate that the amount of water consumed and used directly and indirectly in vehicle manufacturing is not insignificant. Furthermore, this water use and consumption are also directly under the control of the OEM and subject of cradle-to-gate inventory and impact studies because OEMs tend to focus on manufacturing activities as a means for the reduction of total water consumption.

In this paper, our goal is to gain better understanding on the magnitude of direct and indirect water consumption and use in vehicle manufacturing on a per-unit (vehicle produced) basis. For that purpose, we compared and analyzed direct water use and consumption data, as well as indirect water consumption due to electricity use, using information reported by 12 OEMs (auto manufacturers) in their annual sustainability reports.

Table 1 Life cycle water consumption of a passenger vehicle (Tejada et al. 2012b)

Life cycle phase	Water consumption (L)	Percentage
Material production	5,569	9.4
Parts production	902	1.5
Vehicle assembly	670	1.1
Use phase	51,965	87.5
End of life	259	0.4
Total	59,365	100

2 Methods

2.1 Sustainability report water data

Automotive manufacturers utilize water in the manufacturing process usually through either in-house parts production (e.g., casting an engine block) or assembly operations (e.g., painting the car body). Our goal is to gain better understanding on the magnitude of direct and indirect water consumption and use in vehicle manufacturing on a per-unit (vehicle produced) basis. Manufacturing (or production) water data from 2006 to 2010 were found in the sustainability reports of 12 different OEMs in several different forms and related to different activities. All collected data are given in Tables A.1, A.2, and A.3 in the Appendix. Seven companies—BMW, Daimler, Ford, GM, Kia, Toyota, and Volkswagen—directly report information on a per-unit basis (e.g., in cubic meter/vehicle). Five companies—BMW, Chrysler, Hyundai, Mazda, and Nissan—directly report water inflows and wastewater discharges. Conversion of these data to a per-unit basis is accomplished by dividing water input and consumption figures by each OEM's annual vehicle production amount using Eqs. (1) and (2).

$$\text{Water Use} \left[\frac{\text{m}^3}{\text{vehicle}} \right] = \frac{\text{Water Input} [\text{m}^3]}{\text{Production} [\# \text{ vehicles}]} \quad (1)$$

$$\begin{aligned} \text{Water Consumption} \left[\frac{\text{m}^3}{\text{vehicle}} \right] \\ = \frac{\text{Water Input} [\text{m}^3] - \text{Water Discharge} [\text{m}^3]}{\text{Production} [\# \text{ vehicles}]} \end{aligned} \quad (2)$$

OEM vehicle production from 2006 to 2010 used for these calculations is given in Table A.4 and, wherever possible, taken from sustainability reports or annual reports published by each company. If not available as stated, production figures from press releases or production statistics from the International Organization of Motor Vehicle Manufacturers' online database were used. All production figures are directly reported with the exception of Daimler's total production. These values are taken as the sum of bus, car, truck, and van production totals for each year.

Only three companies—Toyota Australia Ltd., Chrysler, and Honda—report water use/consumption data directly attributable to nonproduction-related activities within the manufacturing process. This is referred to as “nonmanufacturing” water use/consumption in this paper, and the data are provided in Table A.5 and Table A.6. Nonproduction water typically includes sanitary water discharge from supporting personnel and activities. The US Department of Energy estimates that a federal office building with 200 people will use 1,230 gal/day of water for domestic needs (23.3 L/day per person). This equates

to 41 % of the office building's potable water use, suggesting that nonproduction water use within the manufacturing life cycle phase could be significant.

For the purpose of this analysis, the combination of a company's manufacturing and nonmanufacturing water footprints is assumed to be equivalent to that of OEM's company-wide water footprint as given by Eq. (3):

$$\begin{aligned} \text{Company wide water footprint} \\ = \text{Manufacturing water footprint} \\ + \text{Nonmanufacturing water footprint} \end{aligned} \quad (3)$$

Thus, knowing the information about any two of a company's activities allows the calculation of a third. This is of interest for comparing water use/consumption of like activities and in discovering how much water is used solely in the production of each vehicle.

2.2 Common sustainability report discrepancies

Three discrepancies often arose in automotive sustainability reports that introduced uncertainty and prevented immediate direct comparisons between the data, namely:

- differences in the definitions of use and consumption,
- dissimilar activity classifications, and
- data contradictions between publications in subsequent years.

In this paper, we do not attempt to resolve all discrepancies but rather maintain the given forms while illuminating those areas where information is missing or suspected.

The classification of water data as either consumption or use given by OEMs is maintained throughout this analysis with two exceptions: Mazda and BMW. Mazda's water inputs are classified in that OEM's sustainability report as consumption figures; we reclassified these as water use. The reason for this change is better understood by considering data from 2010 when Mazda reports a company-wide *water consumption* of 15,269,000 m³ and a *wastewater discharge* of 7,607,000 m³ (Mazda Motor Corporation 2011). It seems unlikely that the company's consumption is greater than its total water discharge—especially since this is not the case for any other OEM examined. Thus, 15,269,000 m³ is maintained as a *water use* value here.

Similarly, BMW's reported consumption values have been reclassified as water use. Again, the reason for our reclassification can be seen by examining data for 2010. In this year, BMW reports 2.31 m³/vehicle (BMW Group 2010) as a per-unit water consumption value. However, taking the company's reported water input of 3,418,816 m³ and dividing the input by a 2010 production of 1,481,253 vehicles (BMW Group 2011) yields a per-unit water use of 2.31 m³/vehicle.

We believe that such reporting issues can be avoided in the future with international reporting standards for water such as ISO 14046. These standards would provide clearer definitions of “water use” and “water consumption,” so that consistency in the classification of water data can be achieved. Noting a current lack of consistency, some water consumption data analyzed could very well be misstated. Daimler, Honda, and Toyota in particular report high consumption values that may, in fact, reflect use.

Water data in this analysis are also categorized by the type of activity where it is used or consumed. Three classifications are typically reported by OEMs including manufacturing, nonmanufacturing, and company-wide water figures. This is of interest for comparing water use in like activities and in discovering how much water is used solely in the production of each vehicle. However, the nonstandardized manner in which companies provide data for only manufacturing, company-wide, or both manufacturing and nonmanufacturing activities requires careful comparison. Ideally, all three should be provided.

This is further complicated by the fact that Honda, Toyota, and Daimler report contradictory values in different years’ sustainability reports. Usually these differences are small (e.g., within 0.5 m³/vehicle), though some manufacturers like Honda report water consumption 15 to 20 million cubic meters higher in its 2010 sustainability report than in its 2011 report. Such differences drastically affect how Honda ranks in its water consumption per vehicle against other competitors.

3 Results and discussion

3.1 Summary of unit basis water data

Water data on a per-unit basis (e.g., in cubic meter/vehicle) are presented in Table 2 for 12 automotive OEMs. The data are organized by water consumption from the lowest to highest. Those companies without consumption data are grouped by water use at the bottom of the table from the lowest to highest. Multiple entries are listed for Honda, Daimler, and Toyota, as these companies report contradictory data in different sustainability reports. Additionally, Honda’s 2010 and Chrysler’s 2010 manufacturing values and Toyota Australia’s company-wide values are calculated using Eq. (3).

The results for all 12 manufacturers vary in terms of both water use and consumption levels and type of activity. In general, water use decline from 2006 to 2010. Mazda is noted as an outlier with a 2010 water use of 83 % higher than Nissan, the next closest OEM. Water use is also generally greater on a per-vehicle basis than water consumption. This is to be expected since the amount of water incorporated into the vehicle or evaporated is much less than that used in the process of making a vehicle.

BMW had the lowest calculated use and consumption values of 2.31 and 0.67 m³/vehicle, respectively. Such low values—as compared to other OEMs—may in part be due to the company’s focus on improving water utilization and efficiency in its local production processes. BMW had a goal of reducing water use and process wastewater by 30 % between 2006 and 2012—a 5 % decline per annum which the company was meeting in 2010 (BMW Group 2010). Efforts include moving to a zero wastewater paint shop in the Regensburg plant and implementing a novel waterless snow-cleaning process for plastic components in the Landshut plant (BMW Group 2010). Other OEMs have introduced similar goals for water reduction including Honda (5 % water use reduction by 2014 (Honda 2011)) and GM (reduce water intensity by 15 % (General Motors Company 2011)), but few have articulated or implemented a strategy to the degree that BMW has shown.

For US auto manufacturers, General Motors and Ford both report similar manufacturing water use of 4.70 and 4.80-m³/vehicle, respectively. Chrysler’s derived manufacturing water use was significantly higher at 6.44 m³/vehicle. However, only Chrysler provided water discharge data with a resulting water consumption of 2.31 m³/vehicle. It is likely that both Ford and General Motors have water consumptions lower than this value, but this is impossible to determine without further knowledge on their water discharge data.

Like US OEMs, German auto manufacturers span the gamut of water use and consumption, with BMW and Volkswagen reporting low to moderate use coupled with low consumption and Daimler reporting the highest water consumption out of the nine OEMs. Japanese manufacturers show similarly scattered results—Honda and Toyota (moderate consumption) compared to Mazda (high use and consumption). This would suggest that the impact of site-specific factors and local water supplies on global water use/consumption is small. Clearly, some OEMs have a competitive advantage in water use/consumption as compared to others in the same general geographical location (e.g., BMW vs. Daimler or Honda vs. Mazda).

3.2 Comparison of averages over the 5-year period

Water use and consumption values are also averaged over the 5-year period for each OEM and are categorized by manufacturing and company-wide activities. These results are shown in Figs. 1 and 2, respectively. The industry average and standard deviation for water use and consumption are also provided in Table 3 for reference. For manufacturing activities, less variance is observed for water use with an industry average of 5.20 m³/vehicle and standard deviation of 1.42 m³/vehicle. Daimler’s water consumption data, however, skew the data set such that the water consumption standard deviation is much higher (i.e., 3.17 m³/vehicle for

Table 2 Reported and calculated water use and consumption data by OEM on a per-unit basis

OEM	Use (m ³ /vehicle)					Consumption (m ³ /vehicle)					Activity
	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010	
BMW	2.99 ^a	2.61 ^a	2.56 ^a	2.56 ^a	2.31 ^a	—	—	—	—	0.67	Mfg
Volkswagen	5.44 ^a	5.38 ^a	5.34 ^a	5.40 ^a	5.01 ^a	1.72 ^a	1.38 ^a	1.46 ^a	1.48 ^a	1.19 ^a	Mfg
Nissan	6.90	6.65	6.16	5.29	6.38	1.83	1.69	1.45	1.76	1.50	Mfg
Chrysler	—	—	—	—	6.44	—	—	—	—	—	Mfg
	—	—	—	—	0.36	—	—	—	—	—	Nonmfg
	—	—	—	—	6.80	—	—	—	—	2.31	Co-wide
Honda 2011	—	—	—	—	—	—	—	2.96	3.92	3.21	Co-wide
Honda 2010	—	—	—	—	—	—	—	—	—	7.16	Mfg
	—	—	—	—	—	—	—	—	—	1.98	Nonmfg
	—	—	—	—	—	4.99	5.79	6.77	11.22	9.14	Co-wide
Toyota 2011	—	—	—	—	—	—	3.60 ^a	3.80 ^a	3.60 ^a	3.70 ^a	Co-wide
Toyota 2010	—	—	—	—	—	4.10 ^a	4.10 ^a	4.60 ^a	4.40 ^a	—	Mfg
Toyota Australia	—	—	—	—	—	4.23	3.72	3.02	3.56	3.84	Mfg
	—	—	—	—	—	—	0.38 ^a	0.23 ^a	0.43 ^a	0.27 ^a	Nonmfg
	—	—	—	—	—	—	4.10	3.25	3.99	4.11	Co-wide
Kia	—	—	—	—	—	—	—	4.80 ^a	4.90 ^a	4.90 ^a	Co-wide
Mazda	22.41	16.24	11.81	15.10	11.68	6.38	9.77	6.12	7.67	5.86	Co-wide
Daimler Cars	—	—	—	—	—	—	6.20 ^a	5.80 ^a	6.00 ^a	—	Mfg
Daimler 2008	—	—	—	—	—	7.26	7.24	—	—	—	Mfg
Daimler 2010	—	—	—	—	—	—	7.73	7.16	8.24	—	Mfg
Daimler 2011	—	—	—	—	—	—	—	7.29	8.16	7.26	Mfg
Daimler Trucks	—	—	—	—	—	—	13.10 ^a	12.20 ^a	18.10 ^a	—	Mfg
General Motors	—	—	—	—	4.70 ^a	—	—	—	—	—	Co-wide
Ford	7.60 ^a	6.20 ^a	5.60 ^a	5.20 ^a	4.80 ^a	—	—	—	—	—	Mfg
Hyundai	6.73	5.65	4.01	3.67	5.42	—	—	—	—	—	Co-wide

Mfg manufacturing, Nonmfg nonmanufacturing, Co-wide company-wide

^a Directly reported water data on a per-unit basis

consumption versus 1.42 m³/vehicle for use). This is another indication that Daimler may in fact be reporting water use data. It should also be noted that with General Motors and Chrysler, only reporting 1 year's worth of water data, these companies' 5-year averages are lower than what was most likely experienced, as most OEMs show declining water figures over the 2006 to 2010 time period.

For company-wide activities, Mazda is an outlier with both water use (9.11 m³/vehicle) and consumption (4.86-m³/vehicle) above one standard deviation from the industry means. Chrysler's company-wide water consumption is also low, falling outside one standard deviation from the mean. Additionally, Fig. 2 differs from Fig. 1 in that water use is observed to have a greater variance than water consumption, which could be explained by differences in process capabilities and methodologies experienced by manufacturers around the globe.

If Daimler and Mazda are excluded from the 5-year averages, the results are reduced to levels consistent with other

OEMs. Without Daimler, average manufacturing water consumption drops from 2.83 to 1.25 m³/vehicle which is more consistent with the averages found for Nissan, Volkswagen, and BMW. Similarly, if Mazda is excluded, average company-wide water consumption drops from 4.86 to 4.29 m³/vehicle. This value may still be high due to Toyota and Honda's classification of data as consumption as opposed to water use. Also without Mazda, average company-wide water use drops to 5.95 m³/vehicle which is much more consistent with all reported water use—both manufacturing and company-wide activities. These modified results are also shown in Table 3.

It is difficult to draw conclusions about nonmanufacturing water use in automotive manufacturing from this analysis. Estimates for the industry are shown in Table 3, too. If Daimler and Mazda are excluded, the data would suggest that nonmanufacturing water consumption would exceed that of water use. A more likely scenario is found when Daimler and Mazda are included. In this case, nonmanufacturing water use exceeds that of water consumption. Additionally,

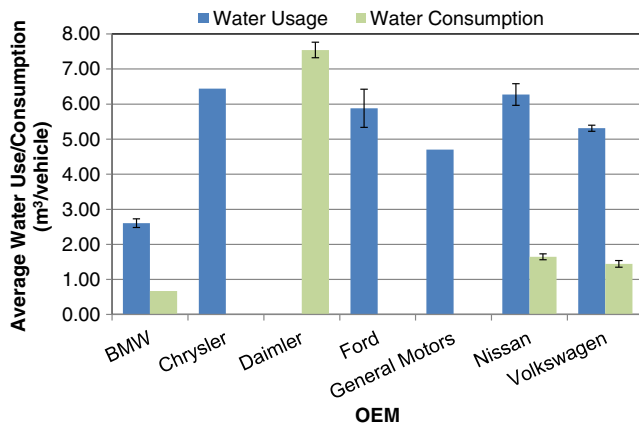


Fig. 1 OEM 5-year average water use/consumption for manufacturing activities. Error bars represent the standard deviation of each company's reported usage/consumption values from 2006 to 2010. An absence of error bars means that only one data point was available

nonmanufacturing use/consumption are smaller than manufacturing use/consumption in this case. While we expect this to be the norm in auto manufacturing, more data and accurate reporting methods are needed before this assumption can be verified.

3.3 Indirect water consumption due to electricity consumption

In addition to direct water use and consumption through manufacturing, research and development, and administrative activities, water is indirectly consumed by automotive companies through their electricity consumption. Automotive sustainability reports that provide water use and consumption data also usually report energy consumption. Table A.7 provides directly reported energy consumption data for available years by OEM. This energy is converted to a megawatt hour/vehicle basis using the production figures listed in Table A.4.

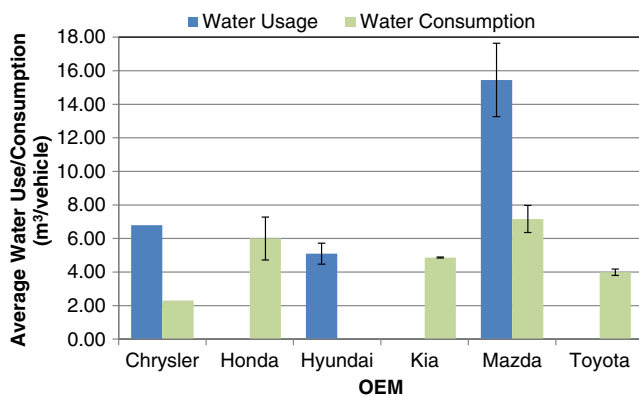


Fig. 2 OEM 5-year average water use/consumption for company-wide activities. Error bars represent the standard deviation of each company's reported usage/consumption values from 2006 to 2010. An absence of error bars means that only one data point was available

Table 3 Industry manufacturing and company-wide activity water use/consumption averages and standard deviations

	Water use (m³/vehicle)	Water consumption (m³/vehicle)
Manufacturing average	5.20	2.83 (1.25 ^a)
Manufacturing standard deviation	1.42	3.17 (0.52 ^a)
Company-wide average	9.11 (5.95 ^a)	4.86 (4.29 ^a)
Company-wide standard deviation	5.55 (1.20 ^a)	1.86 (1.56 ^a)
Estimated nonmanufacturing average	3.91 (0.75 ^a)	2.03 (3.04 ^a)

^a Averages excluding Daimler and Mazda

Water consumption values for several fuel types used in electricity generation including coal, natural gas, nuclear, hydroelectric, and other types of power are provided in Table 4. These values are based on averages for the USA to gain a general understanding on the impact of electricity consumption on water consumption. Table 4 also shows that hydroelectric power consumes significantly more water than other energy sources due to the large evaporative losses from hydropower lakes. This is potentially contentious, and one can argue that there are alternative ways to allocated evaporative losses from hydropower lakes to electricity production, agriculture, and tourism, among others. For this reason, we consider water consumption due to electricity consumption both with and without hydroelectric power.

Data from the US Energy Information Administration (EIA) were also used to develop water consumption figures in liter per kilowatt hour for different electricity generation mixes in different regions of the world. North America, Europe, the USA, Japan, and South Korea were examined in addition to a world average due to select region-specific energy consumption data available from automotive sustainability reports. The resulting indirect water consumptions due to electricity generation in these regions are provided in Tables 5 and 6. Hydroelectric power increases the water consumption of the electricity mix significantly. Without hydroelectric power, water consumption ranges between 0.69 and 1.03 L/kWh for the regions examined. By comparison, freshwater consumption values used in the Argonne

Table 4 Average water consumption for electricity generation (Fthenakis and Kim 2010; Feeley III et al. 2008; Gleick 1994; Yen and Bras 2012; Harto et al. 2010; Tejada et al. 2012a)

Electricity source	Water consumption (L/kWh)
Coal	0.871
Natural gas	0.547
Nuclear power	1.643
Hydroelectric	17.000
Other (solar)	0.023

Table 5 Water consumption for electricity generation by region—including hydroelectric power (EIA 2011)

Electricity source	OECD Americas	OECD Europe	USA	Japan	South Korea	World
Coal (%)	41.8	25.0	48.2	26.1	42.5	40.2
Natural gas (%)	21.1	24.5	21.4	26.8	18.9	21.7
Nuclear power (%)	17.9	25.6	19.6	24.1	34.1	13.6
Hydroelectric (%)	13.8	15.1	6.2	7.4	0.7	16.3
Other (renewables) (%)	1.6	3.2	1.8	2.1	0.2	1.4
Water consumption (L/kWh)	3.12	3.34	1.91	2.02	1.16	3.47

National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (including hydroelectric power) range between 0.26 and 0.64 gal/kWh (0.98–2.42 L/kWh) with an average of 1.5 L/kWh (Wu 2011). This difference is due predominantly to GREET's use of a lower hydroelectric power water consumption of 7.5 L/kWh (compared to 17.0 L/kWh referenced in Table 4). These GREET values are representative of the 17 states responsible for 65 % of electricity production in the USA.

In the GREET Model, energy consumption during the VMA stage of the vehicle life cycle for a single vehicle is 33,924 MJ (Sullivan 2010). This includes activities such as material transformation (19,340 MJ), vehicle painting (4,167 MJ), HVAC and lighting (3,335 MJ), and heating (3,110 MJ) among others. By comparison, average energy consumption across all OEMs is 11,557 MJ/vehicle based on the information in Table A.7. This is still viewed as

Table 6 Water consumption for electricity generation by region—excluding hydroelectric power (EIA 2011)

Electricity Source	OECD Americas	OECD Europe	USA	Japan	South Korea	World
Coal (%)	41.8	25.0	48.2	26.0	42.5	40.2
Natural gas (%)	21.1	24.5	21.4	26.8	18.9	21.7
Nuclear power (%)	17.9	25.6	19.6	24.1	34.1	13.6
Hydroelectric	–	–	–	–	–	–
Other (renewables) (%)	1.6	3.2	1.8	2.1	0.2	1.4
Water consumption (L/kWh)	0.77	0.77	0.86	0.77	1.03	0.69

comparable to the GREET model, however, because the automotive sustainability reports exclude energy consumption due to raw material transformation. If this consumption is excluded from the GREET Model, energy consumption for this model becomes 14,584 MJ/vehicle, a difference of only 3,027 MJ from our calculated average.

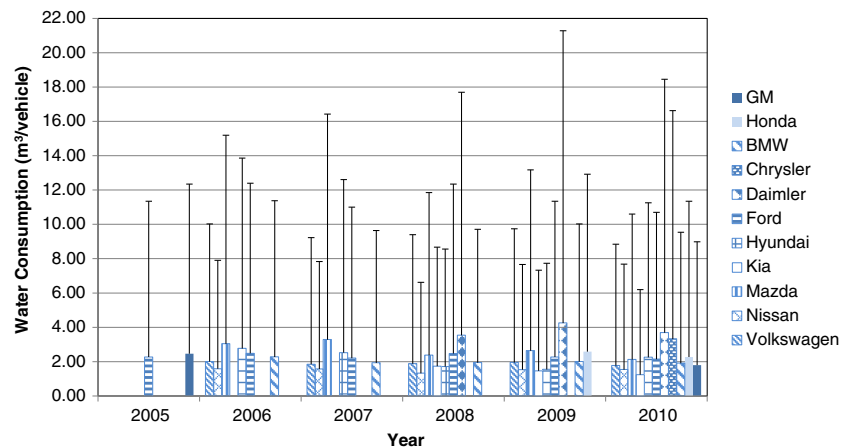
Global indirect water consumption is calculated for each OEM by multiplying the total global energy consumption (in megawatt hour/vehicle) by the water consumption (in liter per kilowatt hour). The results are provided in Fig. 3. In this calculation, it is assumed that all energy consumption is electricity consumption (e.g., all energy consumption can be converted to water consumption assuming that the electricity generation figures are provided). This was assumed due to the nature of energy data provided in OEM sustainability reports. Some manufacturers provide electricity consumption figures as a percentage of total energy consumption as follows: Kia (36 %), Mazda (67 %), Volkswagen (48 %), Chrysler (39 %), and Daimler (43 %). Others like Ford, Hyundai, and Nissan only relate total energy consumption. Thus, while not all energy consumption translates directly to electricity consumption, this analysis does develop an upper limit on indirect water consumption through electricity consumption. This is a more conservative approach when considering the variety among manufacturers listed above.

Figure 3 shows that indirect water consumption can exceed direct water consumption, especially when hydroelectric consumption of 17 L/kWh (values indicated with error bars) is included. In this case, indirect water consumption ranges from 6.20 to 21.28 m³/vehicle, approximating the direct water use reported by Mazda which were the highest direct water use figures reported by any OEM. Mazda's direct water use ranged from 11.68 to 22.41 m³/vehicle. The second highest direct water use was by Chrysler at only 6.8 m³/vehicle. If hydroelectric power is excluded, indirect water consumption is still significant, approximating direct water consumption for most manufacturers. For example, Volkswagen reports a 2010 direct water consumption of 1.19 m³/vehicle, while their 2010 indirect water consumption in Fig. 3 was calculated as 1.77 m³/vehicle.

A few manufacturers provide regional energy consumption data which allow comparisons based on more localized electricity mixes. Regional data are available for Nissan and Honda in Japan, Hyundai in South Korea, Nissan and Toyota in North America, and Nissan in Europe. These directly reported figures are provided in Table A.8.

Using the same procedure described for global energy consumption and making the same assumptions, indirect water consumption on the basis of cubic meter per vehicle is calculated and provided in Fig. 4. The effects of hydroelectric power are somewhat less pronounced for this

Fig. 3 Global indirect water consumption due to energy consumption. *Error bars* represent value (in liter per kilowatt hour) of water consumption when hydroelectric consumption of 17.0 L/kWh is included in the estimate of indirect water consumption



regional case (average water consumption of 6.42 m³/vehicle as compared to 11.13 m³/vehicle for the global scenario). There is little difference in water consumption, however, between the regional and global case when hydroelectric power is excluded (e.g., 2.35 m³/vehicle for regional compared to 2.22 m³/vehicle for global). This indicates that the global indirect water consumption found for all OEMs based on energy consumption is a good approximation—even when averaging electricity mixes globally instead of considering localized cases.

Table 7 provides a comparison of global direct and indirect water consumption (excluding hydroelectric power) for 2010. It suggests that in some cases, indirect water consumption can exceed direct water consumption as is shown for BMW, Chrysler, Nissan, and Volkswagen. This is also potentially true for Ford, GM, and Hyundai as only water use figures are available from these OEMs. Though the average direct water consumption is higher than indirect consumption (3.36 and 2.21 m³/vehicle, respectively), the direct consumption average is potentially skewed by these three water use figures.

The implications of this analysis for automotive manufacturers are that indirect water consumption due to electricity can be on par with and sometimes exceed direct water

consumption. Thus, it is important that OEMs focus on minimizing their electricity consumption in conjunction with reducing direct water consumption in manufacturing and nonmanufacturing activities. Decreasing electricity consumption could have a similar impact to decreasing direct water consumption.

4 Uncertainties and limitations

Uncertainties in direct water use/consumption can arise from OEM reporting and classification errors, inclusion of parts production water figures, and variability of local water resources. As has already been highlighted, water data were limited to that available in OEM sustainability reports. Thus, the presented results depend on the quality and thoroughness of each auto manufacturer. It can be difficult to interpret

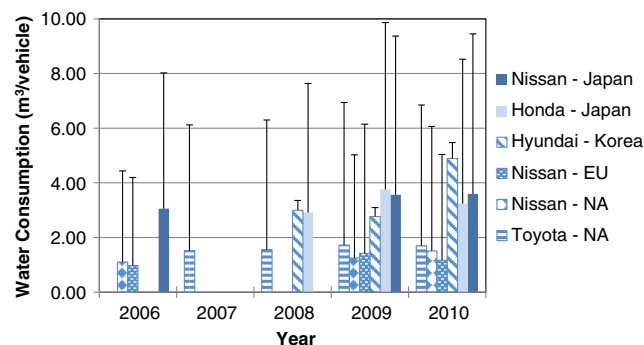


Fig. 4 Regional indirect water consumption due to energy consumption. *Error bars* represent value (in liter per kilowatt hour) of water consumption when hydroelectric consumption of 17.0 L/kWh is included in the estimate of indirect water consumption

Table 7 Comparison of 2010 global direct and indirect water use and consumption excluding hydroelectric power

OEM	2010 Global water use and consumption in m ³ /vehicle			Indirect–direct consumption difference (m ³ /vehicle)
	Direct use	Direct consumption	Indirect consumption	
BMW	2.31	0.67	1.91	+1.24
Chrysler	6.80	2.31	3.32	+1.01
Daimler		7.26	3.69	−3.57
Ford	4.80		2.41	
GM	4.70		1.80	
Honda		3.21	2.27	−0.94
Hyundai	5.42		2.25	
Kia		4.9	1.24	−3.66
Mazda	11.68	5.86	2.12	−3.74
Nissan	6.38	1.5	1.54	+0.04
Volkswagen	5.01	1.19	1.77	+0.58
Average	5.89	3.36	2.21	−1.13

whether a given value is all-encompassing of a company's activity-specific water footprint or limited by incomplete data collection, inclusion of suppliers' water use/consumption, or misclassification of water resources (e.g., labeling use as consumption). Data availability was also limited for some manufacturers across the 5-year period of this study, making it difficult to draw conclusions about potentially significant segments of the water footprint such as nonmanufacturing water use.

Water availability varies significantly from location to location, introducing site-specific factors such as differing process technologies across manufacturing locations or employee habits at nonmanufacturing sites. Water scarcity for each OEM based on concentration of operations was not examined in this study and may have some impact on the end use/consumption reported. Future work will focus on updating the benchmarks developed here to correct for such site-specific factors.

Uncertainty also exists in the determination of indirect water consumption due to electricity generation. A simplifying assumption was made that all energy consumption is electricity consumption—a situation that may not be entirely accurate as different OEMs will have different energy mixes. Additionally, uncertainty arises in the value of water consumption assigned to hydroelectric power and whether or not hydroelectric power water consumption should be considered. This water consumption from hydropower bears further investigation. Dependent on the locality, evaporation rates from hydropower lakes can vary at an order of magnitude (Torcellini et al. 2003). For example, evaporation rates for the State of Georgia are 179 L/kWh versus 12 L/kWh for the State of Washington (Torcellini et al. 2003; Yen and Bras 2012). In this article, we assume that the exclusion of hydroelectric power is more representative of actual water consumption from the electricity generation process due to similarities with the GREET Model. If hydroelectric power is to be included, however, we maintain a figure of 17.0 L/kWh for hydroelectric power water consumption consistent with that of Tejada et al. These authors found the difference between US electricity grid mixes with and without hydroelectric power to be 1.41 L/kWh (2.23 L/kWh with hydroelectric power–0.82 L/kWh without) (Tejada et al. 2012a). In Tables 5 and 6, this difference is 2.35 L/kWh (3.12–0.77 L/kWh) for OECD Americas and 2.78 L/kWh (3.47–0.69 L/kWh) for the world average. While our differences in water consumption with and without hydroelectric power are somewhat greater, they also represent a larger aggregate region.

Going forward, it is expected that OEMs will provide more complete water data as standards such as ISO 14046 are released. However, this analysis can be used as an initial benchmark for determining manufacturing and company-wide direct and indirect water use/consumption in automotive manufacturing. Future work will focus on updating this benchmark as more data become available. Nonmanufacturing water

data will also be examined to identify the effects of research versus office building activities on an automotive company's water footprint.

5 Conclusions

In this paper, our goal is to gain better understanding on the magnitude of direct and indirect water consumption and use in vehicle manufacturing on a per-unit (vehicle produced) basis. For that purpose, we compared and analyzed direct water use and consumption data, as well as indirect water consumption due to electricity use, using information reported by 12 OEMs (auto manufacturers) in their annual sustainability reports.

The analysis shows that while OEM sustainability report water data lack completeness and can vary widely across manufacturers, general trends are observable. Between 2006 and 2010, most OEMs exhibited a decline in water use and consumption. As expected, water use also tends to exceed water consumption. Results show that average water use was 5.20 and 5.95 m³/vehicle for manufacturing and company-wide activities, respectively (excluding outliers), with the corresponding standard deviations of 1.42 and 1.20 m³/vehicle. Similarly, average water consumption was 1.25 and 4.29 m³/vehicle for manufacturing and company-wide activities, respectively (excluding outliers), with the corresponding standard deviations of 0.52 and 1.56 m³/vehicle. These values can potentially be used to estimate water use/consumption for automotive manufacturing where data are unavailable.

Additionally, this analysis examined the effects of indirect water use and consumption due to electricity generation on auto manufacturers' water footprints. It was found that the average indirect water consumption due to electricity consumption is 2.21 m³/vehicle. Thus, the amount of indirect water consumption due to electricity use equals and, in some cases, even exceeds the amount of direct water consumption in manufacturing. Thus, the effect of electricity, different generation technologies, and local grid mixes are important and should be taken into account in water footprint and water-focused LCI/LCA studies. OEMs that focus on minimizing electricity consumption in conjunction with direct water consumption can realize more significant reductions in their overall water footprints than those that focus only on minimizing direct water consumption. Standards such as ISO 14046 are crucial to this entire process so that interested parties can better understand how water is being used in automotive manufacturing.

Acknowledgments The material presented in this manuscript is based on research done within the Sustainable Design and Manufacturing Program of the Manufacturing Research Center at the Georgia Institute of Technology. The authors would like to thank all those who have contributed their invaluable input and support, including but not limited to David Berdish, Thomas Niemann, Tim Wallington, Sherry

Mueller, Hyung Chul Kim, and Wulf-Peter Schmidt from the Ford Motor Company.

References

- Berger M, Warsen J, Krinke S, Bach V, Finkbeiner M (2012) Water footprint of European cars: potential impacts of water consumption along automobile life cycles. *Environ Sci Technol* 46:4091–4099
- Blackhurst M, Hendrickson C, Sels I, Vidal J (2010) Direct and indirect water withdrawals for U.S. industrial sectors. *Environ Sci Technol* 44:2126–2130
- BMW Group (2010) Sustainability value report 2010. Bayerische Motoren Werke, AG, Munich
- BMW Group (2011) Annual report 2010. Bayerische Motoren Werke, Munich
- EIA (2011) International energy outlook 2011. EIA, Washington, DC
- Feeley TJ III, Skone TJ, Stiegel GJ Jr, McNemar A, Nemeth M, Schimmoller B, Murphy JT, Manfredo L (2008) Water: a critical resource in the thermoelectric power industry. *Energy* 33(1):1–11
- Fthenakis V, Kim HC (2010) Life-cycle uses of water in U.S. electricity generation. *Renew Sust Energ Rev* 14(7):2039–2048
- General Motors Company (2011) Sustainability in motion: general motors sustainability report. General Motors Company, Detroit
- Gleick PH (1994) Water and energy. *Annu Rev Energ Env* 19(1):267–299
- Harto C, Meyers R, Williams E (2010) Life cycle water use of low-carbon transport fuels. *Energy Policy* 38(9):4933–4944
- Honda (2011) Global environmental impact. <http://world.honda.com/environment/currentinitiatives/impact.html>. Accessed 15 Nov 2011
- ISO (2011) ISO14046 water footprint working draft 2.1-17. ISO, Geneva
- Mazda Motor Corporation (2011) Sustainability report 2011. CSR and Environment Department, Hiroshima
- Owens JW (2002) Water resources in life-cycle impact assessment. *J Ind Ecol* 5(2):37–54
- Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. *Environ Sci Technol* 43(11):4098–4104
- Raimbault M, Humbert S (2011) ISO considers potential standard on water footprint. International Organization for Standardization. http://www.iso.org/iso/isofocusplus_bonus_water-footprint. Accessed February 18 2012
- Schweimer GW, Levin M (2000) Sachbilanz des Golf A4 (life cycle inventory for the Golf A4). Volkswagen AG, Wolfsburg
- Sullivan JL, Burnham A, Wang M (2010) Energy-consumption and carbon-emission analysis of vehicle and component manufacturing (trans: Division ES). Argonne National Laboratory, Argonne
- Tejada F, Bras B, Guldberg T (2012a) Direct and indirect water consumption in vehicle manufacturing. In: ASME 2012 international design engineering technical conferences and computers and information in engineering conference, Chicago, IL
- Tejada F, Zullo J, Yen J, Guldberg T, Bras B (2012b) Quantifying the life cycle water consumption of a passenger vehicle. In: Proceedings of 2012 SAE world congress conference and exposition. SAE International, Troy
- Torcellini P, Long N, Judkoff R (2003) Consumptive water use for U.S. power production. National Renewable Energy Laboratory, Golden
- Wu M, Peng MJ (2011) Developing a tool to estimate water use in electric power generation in the United States (trans: Division ES). Argonne National Laboratory, Argonne
- Yen J, Bras B (2012) A system model for assessing vehicle use-phase water consumption in urban mobility networks. *Energy Policy* 51:474–492